Comet/asteroid **O**rbit **D**etermination and **E**phemeris **S**oftware

by Jim Baer

In support of current minor planet surveys, CODES combines an n-body numerical integrator with a Graphical User Interface to provide the following capabilities:

- Orbit determination based on optical and radar observations;
- Calculation of topocentric or geocentric ephemerides;
- Identification of known minor planets which most closely match a set of observations;
- Linear and non-linear collision analysis.
- N-body integrator accounts for cometary thrusting (if applicable), solar radiation pressure, solar oblateness, and gravitational perturbations (including relativistic effects) from the Sun, nine planets, Earth's Moon, and up to 300 asteroids.

CODES is an object-oriented application

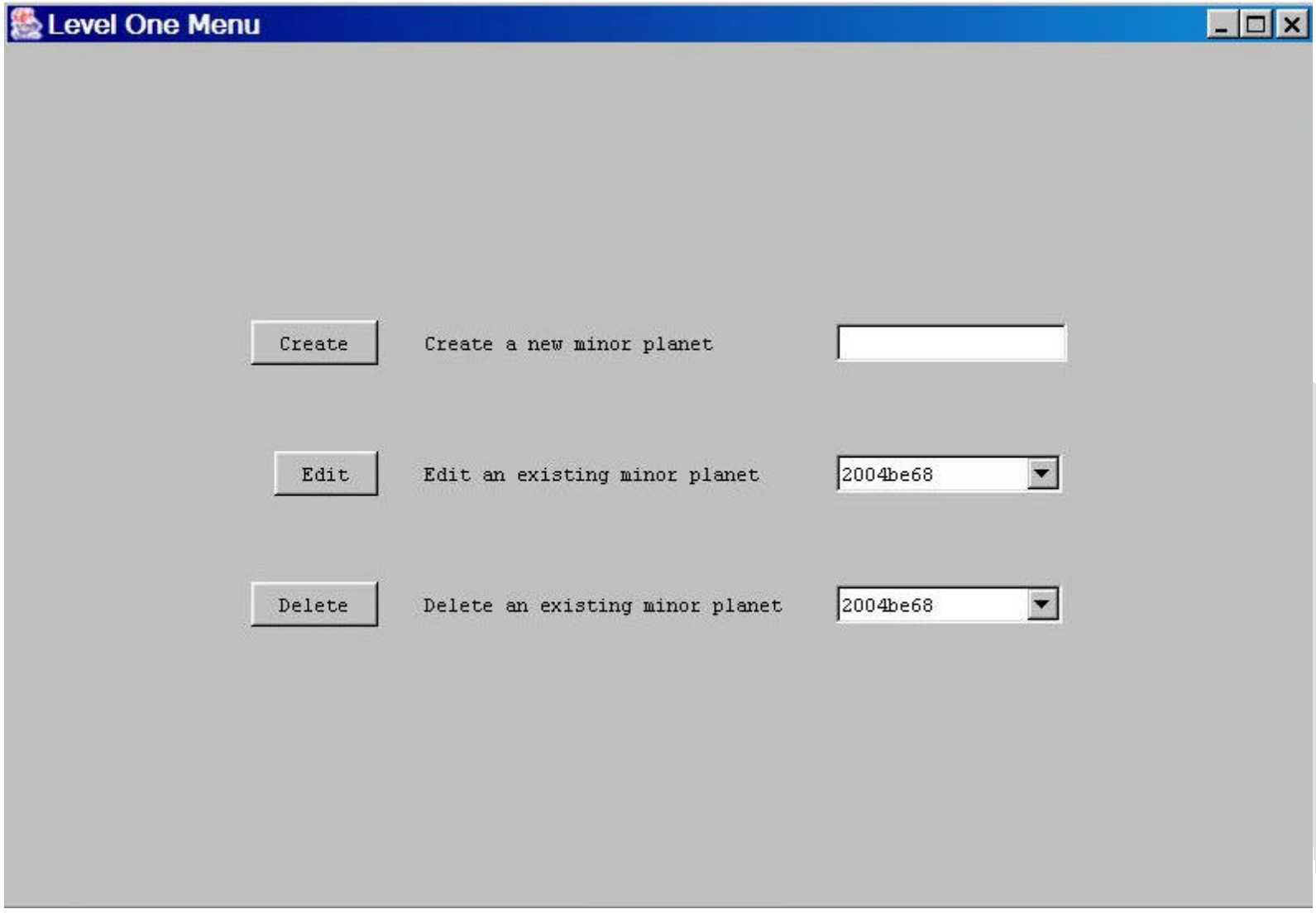
Level One Menu:

- Create, Delete, or Open instances of the class “MinorPlanet”

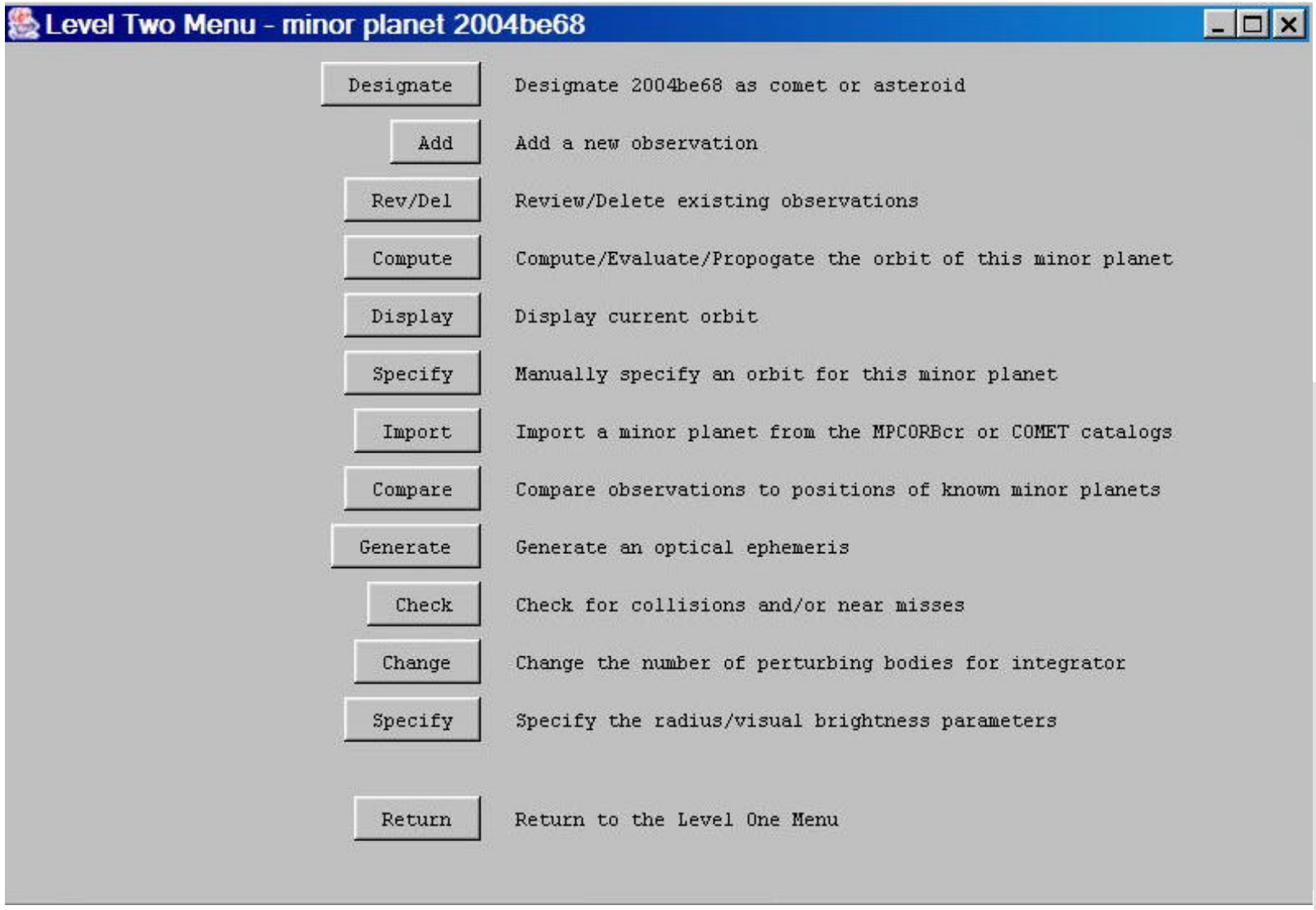
Level Two Menu:

- Add attributes (observations)
- Derive additional attributes (orbital elements, ephemerides, collision analysis)

Level One Menu



Level Two Menu



Level Two Menu: *Designate the minor planet as a comet or asteroid*

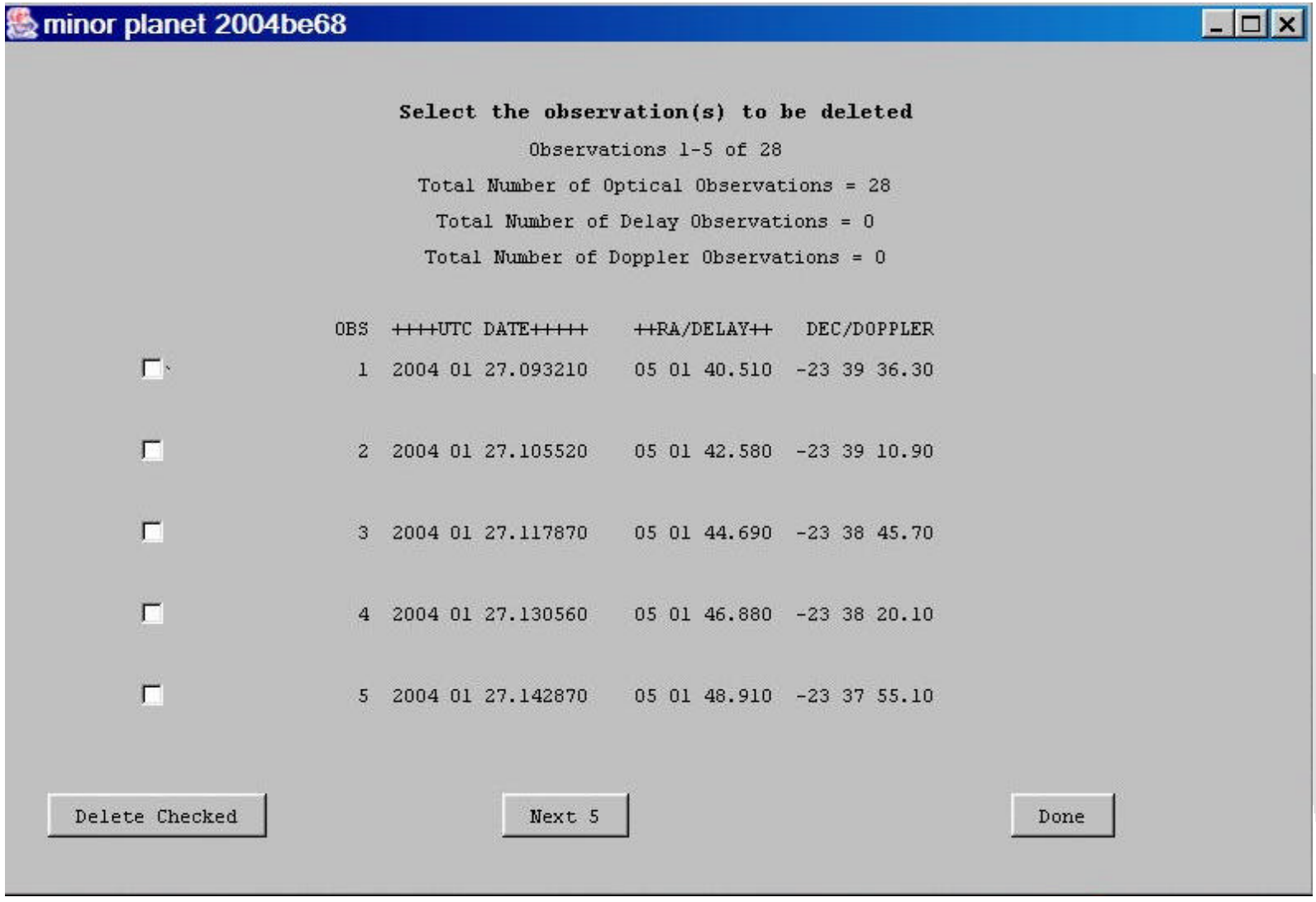
- Should be the first change made to a new minor planet file
- Critically impacts:
  - Least-squares best-fit orbit
  - Processing visual magnitude data
  - Minor Planet Center (MPC) catalog search
  - Orbital element display
  - Use of cometary thrust in numerical integrator

Level Two Menu: *Adding an Observation*

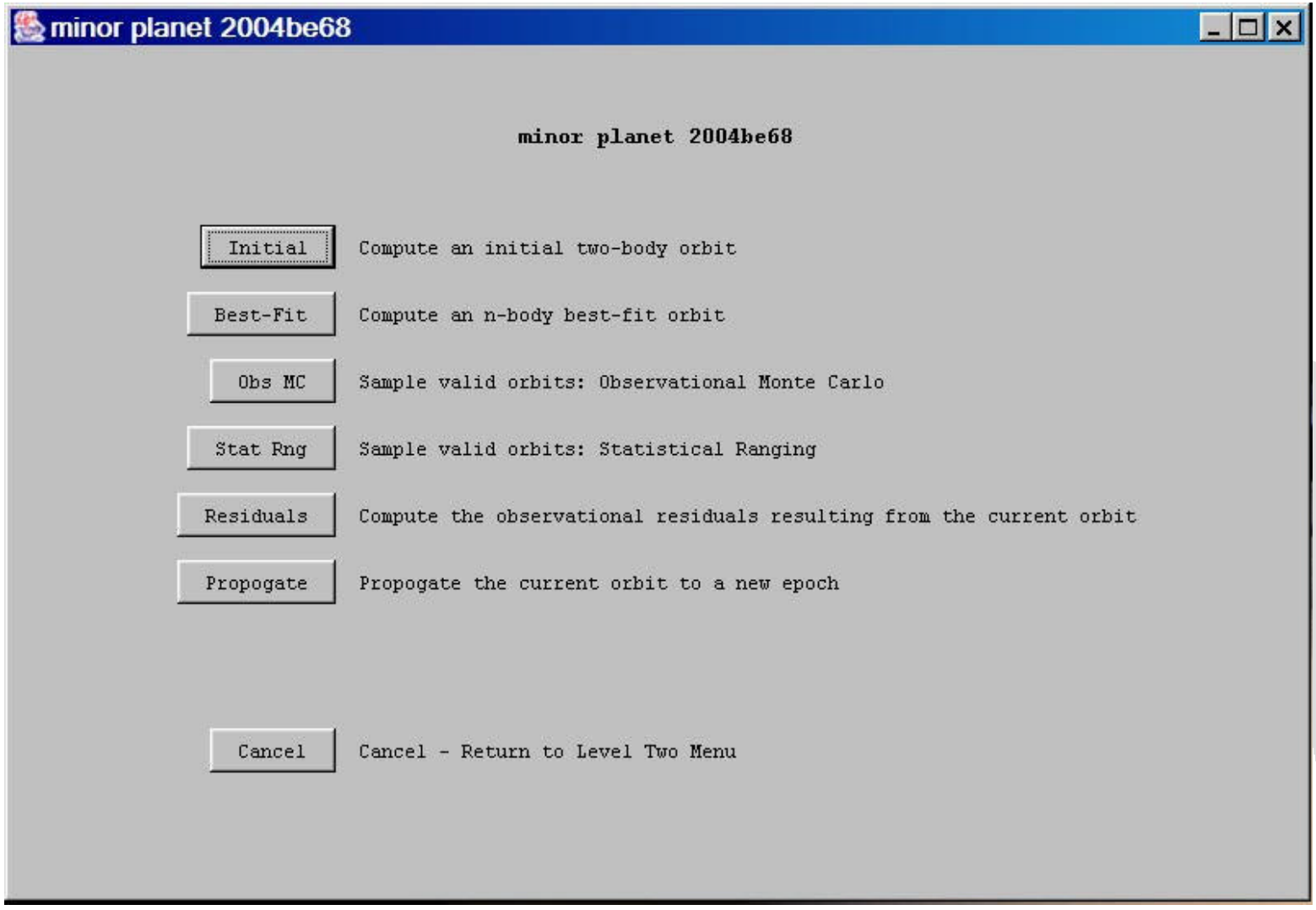
- Manual entry of ground-based optical observation
- Manual entry of radar observation
- Parse and process Minor Planet Electronic Circular (MPEC) or Minor Planet Center Observation (MPCOBS) file
- Parse and process Near Earth Object Dynamic Site (NEODyS) ASCII observation file
- If International Earth Rotation Service (IERS) Earth Orientation Parameter (EOP) file not available for observation epoch, manual entry or default EOPs used

note: observations supported in period 1900-2200

Level Two Menu: *Review/Delete Existing Observations*


minor planet 2004be68
Select the observation(s) to be deleted
Observations 1-5 of 28
Total Number of Optical Observations = 28
Total Number of Delay Observations = 0
Total Number of Doppler Observations = 0
OBS ++++UTC DATE+++++ ++RA/DELAY++ DEC/DOPPLER
1 2004 01 27.093210 05 01 40.510 -23 39 36.30
2 2004 01 27.105520 05 01 42.580 -23 39 10.90
3 2004 01 27.117870 05 01 44.690 -23 38 45.70
4 2004 01 27.130560 05 01 46.880 -23 38 20.10
5 2004 01 27.142870 05 01 48.910 -23 37 55.10
Delete Checked
Next 5
Done

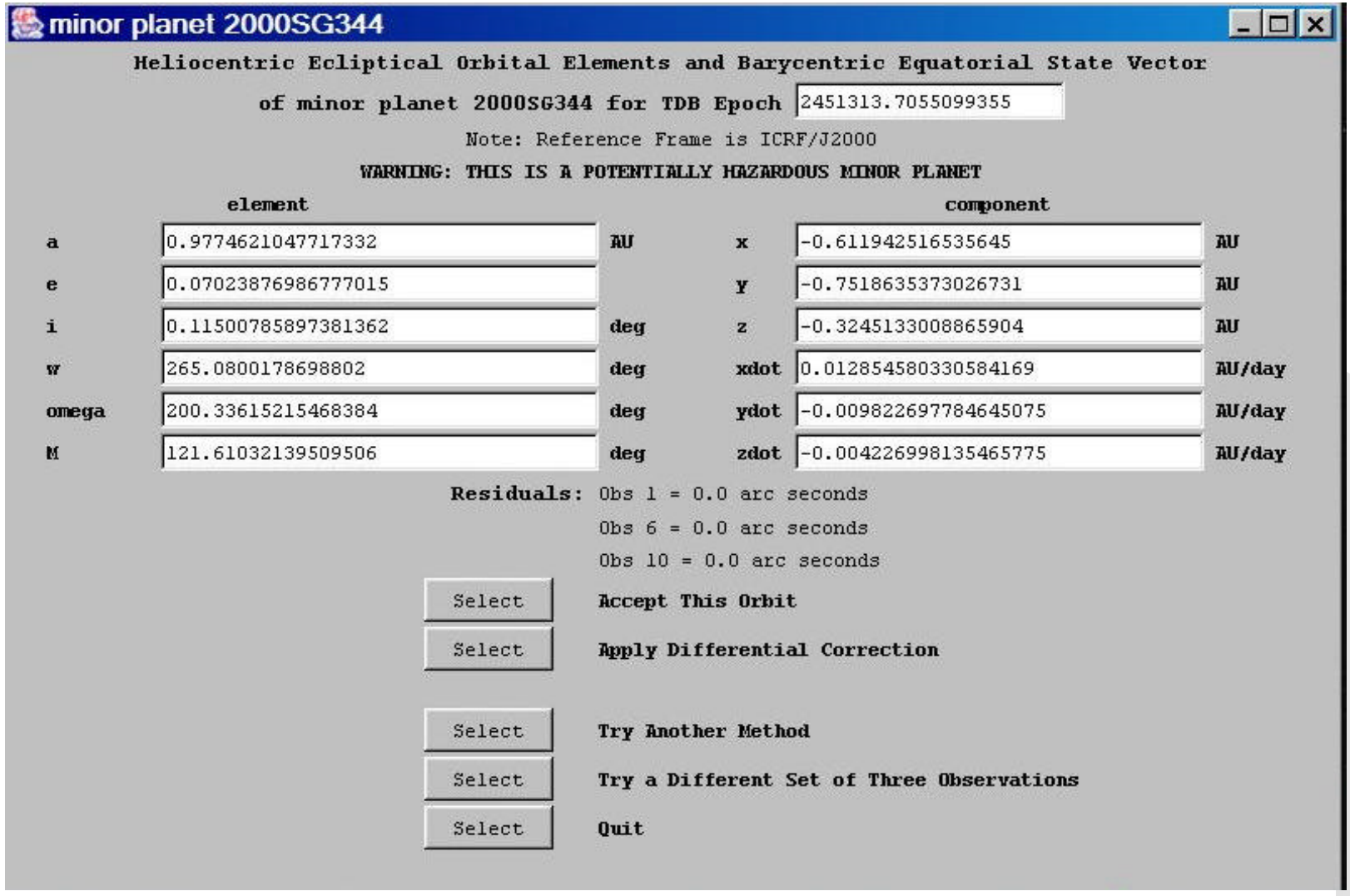
Level Two Menu: *Compute/Evaluate/Propogate the orbit of this minor planet*



Level Two Menu: *Compute an initial two-body orbit*

- Gauss Method
- Conditioned Gauss (semi-major axis constrained)
- Laplace Method
- Herget's Method (slant-range constrained)
- Statistical Ranging (slant-range sampling) (Note: This algorithm is located in a different menu, but is a highly-effective method of initial orbit determination, especially for very short arcs)

Level Two Menu: *Compute an initial two-body orbit (results)*


minor planet 2000SG344
Heliocentric Ecliptical Orbital Elements and Barycentric Equatorial State Vector
of minor planet 2000SG344 for TDB Epoch 2451313.7055099355
Note: Reference Frame is ICRF/J2000
WARNING: THIS IS A POTENTIALLY HAZARDOUS MINOR PLANET
element
component
a 0.9774621047717332 AU
e 0.07023876986777015
i 0.11500785897381362 deg
w 265.0800178698802 deg
omega 200.33615215468384 deg
M 121.61032139509506 deg
x -0.611942516535645 AU
y -0.7518635373026731 AU
z -0.3245133008865904 AU
xdot 0.012854580330584169 AU/day
ydot -0.009822697784645075 AU/day
zdot -0.004226998135465775 AU/day
Residuals: Obs 1 = 0.0 arc seconds
Obs 6 = 0.0 arc seconds
Obs 10 = 0.0 arc seconds
Select Accept This Orbit
Select Apply Differential Correction
Select Try Another Method
Select Try a Different Set of Three Observations
Select Quit

Level Two Menu: *Compute an n-body best-fit orbit*

- Least squares with n-body numerical integration
  - cometary thrusting (if applicable)
  - solar radiation pressure
  - solar oblateness
  - gravitational perturbations (including relativistic terms) from the Sun, nine planets, Earth's Moon, and up to 300 asteroids
- Refines
  - an initial two-body orbit
  - a statistical ranging orbit
  - an imported orbit (MPCORBcr file)
  - a user-specified orbit
- Allows observations to be excluded based on excessive chi or residuals

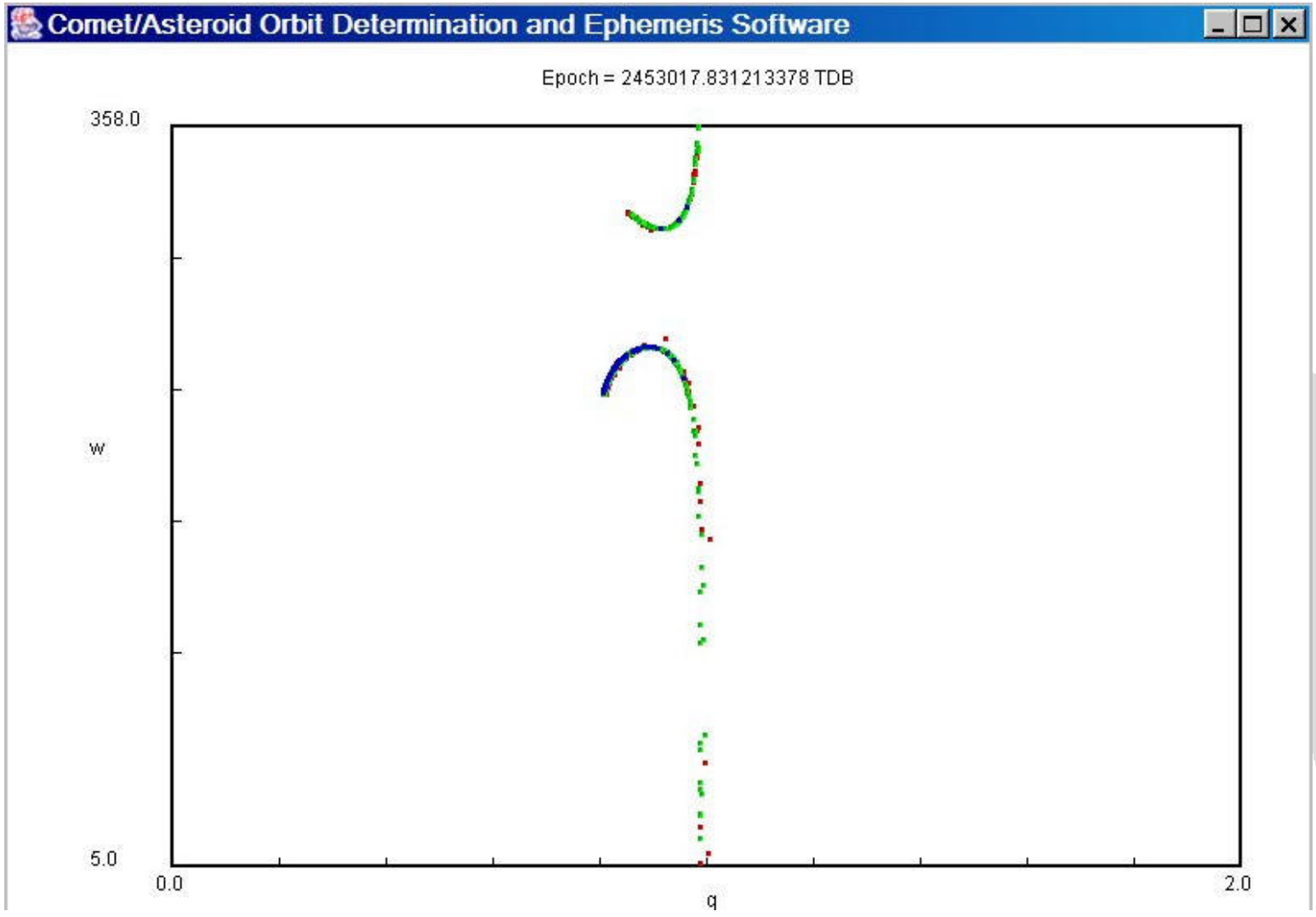
Level Two Menu: *Compute an n-body best-fit orbit (results)*

- state vector plus covariances
- derived orbital elements plus covariances
- residuals for each observation
- visual absolute magnitude and slope parameter (if apparent magnitude observations are available)
- estimate of the minor planet's radius (asteroids only, if visual absolute magnitude and slope parameter are available)
- Minimum Orbital Intersection Distance (NEOs only)
- Warning for Potentially-Hazardous Objects
- SkyMorph parameters formatted for easy input
- output to screen and text file

Level Two Menu: *Sample Valid Orbits: Observational Monte Carlo*

- If least-squares converges but observed arc is very short, the covariance ellipsoid may not accurately represent the solution space; this option directly samples the space of valid orbits
  - Add Gaussian uncertainty to each observation
  - Apply least-squares to derive variant orbit
  - Default setting: Create 100 variant orbits
- Variant orbits can be displayed in color-coded scatterplots to illustrate solution space
  - q vs. e
  - q vs. i
  - q vs. w
  - q vs. Ω
  - q vs. M
- Variant orbits can be used
  - to generate ephemeris scatterplots for precovery/recovery
  - for Monte Carlo collision analysis

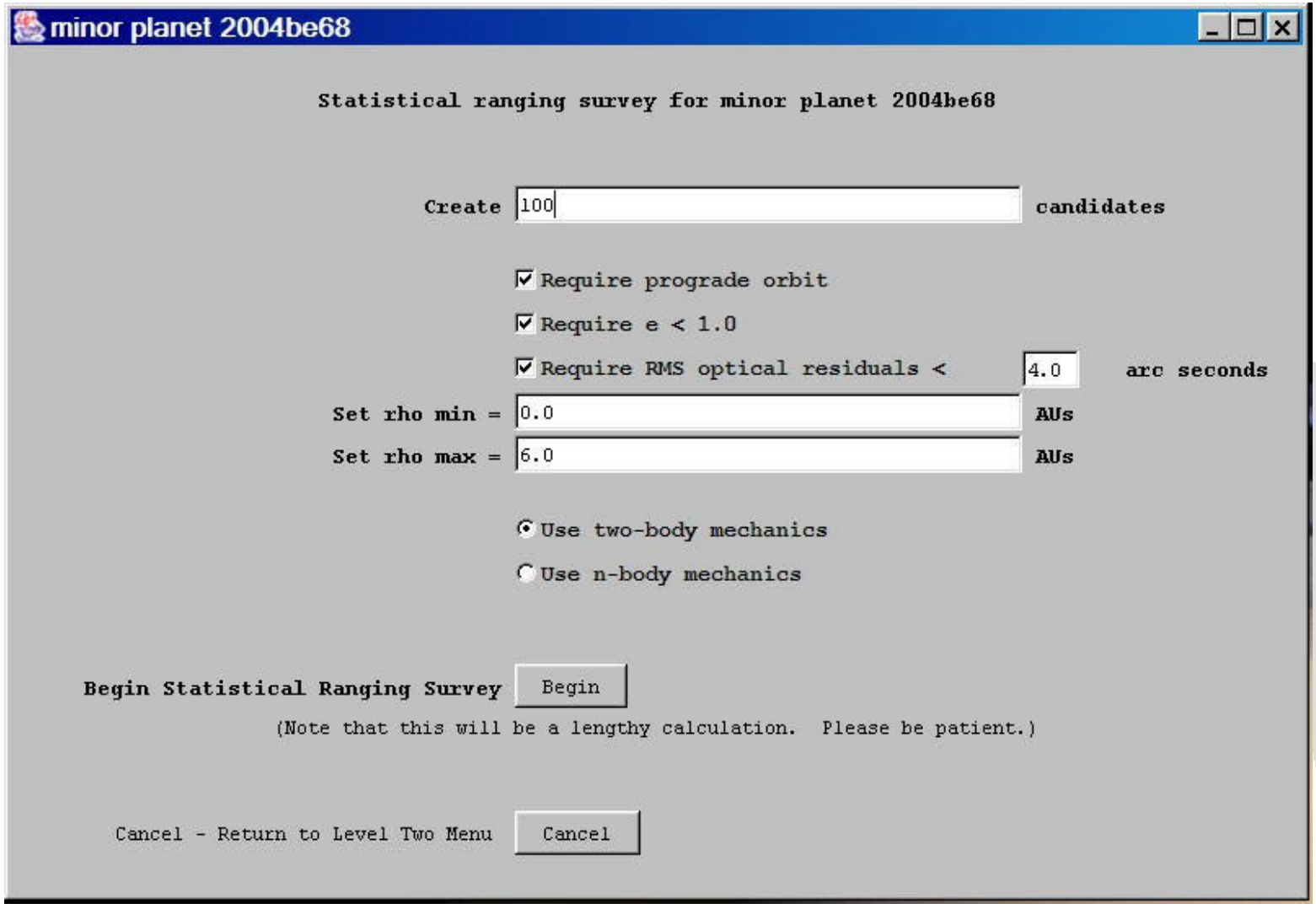
Level Two Menu: *Sample Valid Orbits: Observational Monte Carlo (cont)*



Level Two Menu: *Sample Valid Orbits: Statistical Ranging*

- Used for very short arcs in place of initial-orbit methods; directly samples the non-linear space of valid orbits
  - Randomly generate slant ranges for first and last observations (based on user-specified min/max slant range)
  - Combine with first/last observations and observer positions to create two position vectors
  - Use Gauss sector-triangle ratios (two-body) or Herget's method (n-body) to derive state vector
  - Compare predicted RA/Decs to observations; accept if RMS residual less than user-specified threshold
- User can optionally require only prograde, elliptical orbits
- User-specified number of variants generated

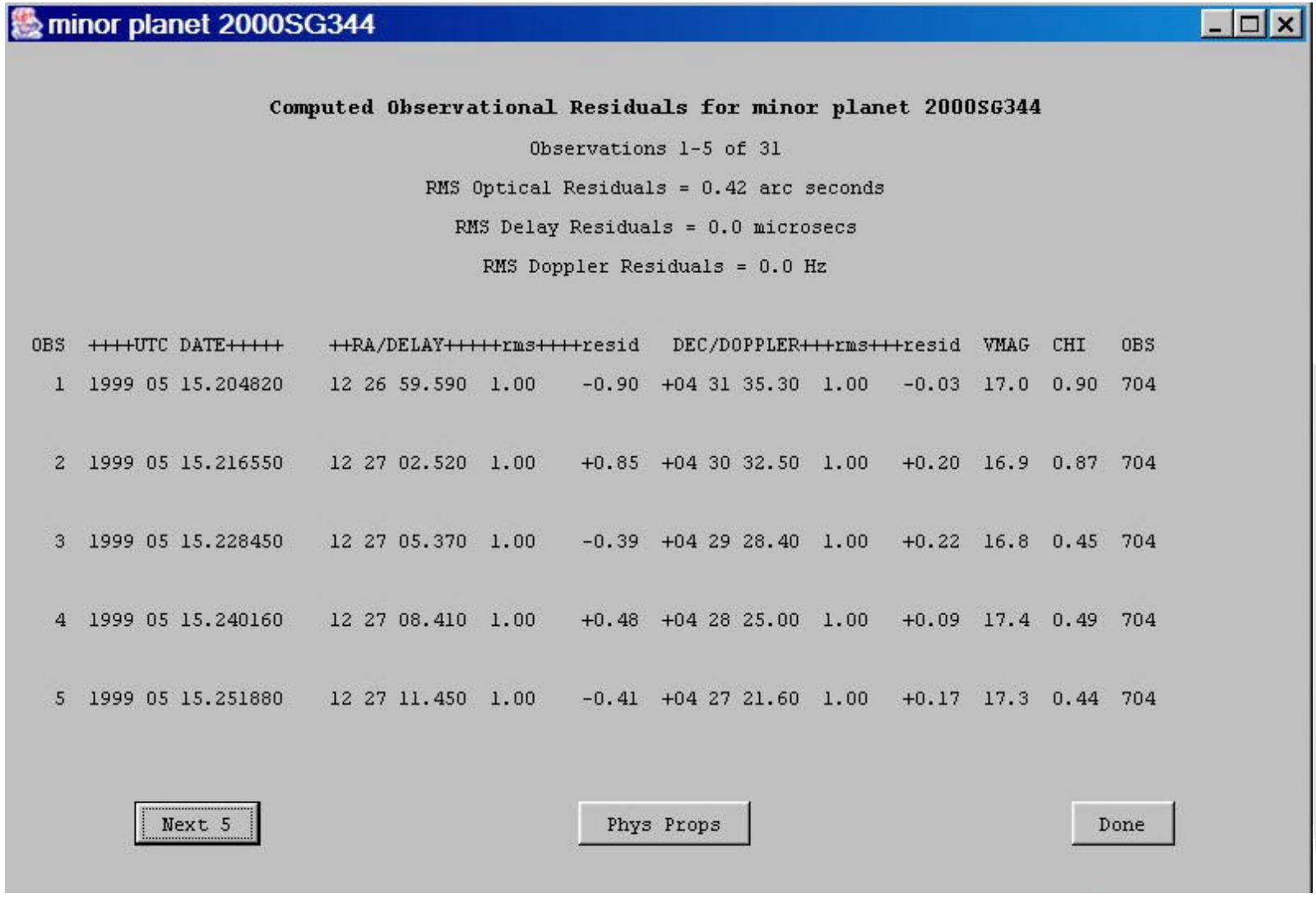
Level Two Menu: *Sample Valid Orbits: Statistical Ranging (cont.)*



Level Two Menu: *Sample Valid Orbits: Statistical Ranging (cont.)*

- Variant orbits can be
  - displayed in color-coded scatterplots to illustrate non-linear solution space
  - used to generate ephemeris scatterplots for precovery/recovery
  - used for Monte Carlo collision analysis
- Only reliable approach for very short-arc cases
  - Reveals multiple solutions
  - Robust orbit and ephemeris uncertainty spaces
  - Allows collision analysis when no best-fit orbit is available

Level Two Menu: *Compute the observational residuals resulting from the current orbit*



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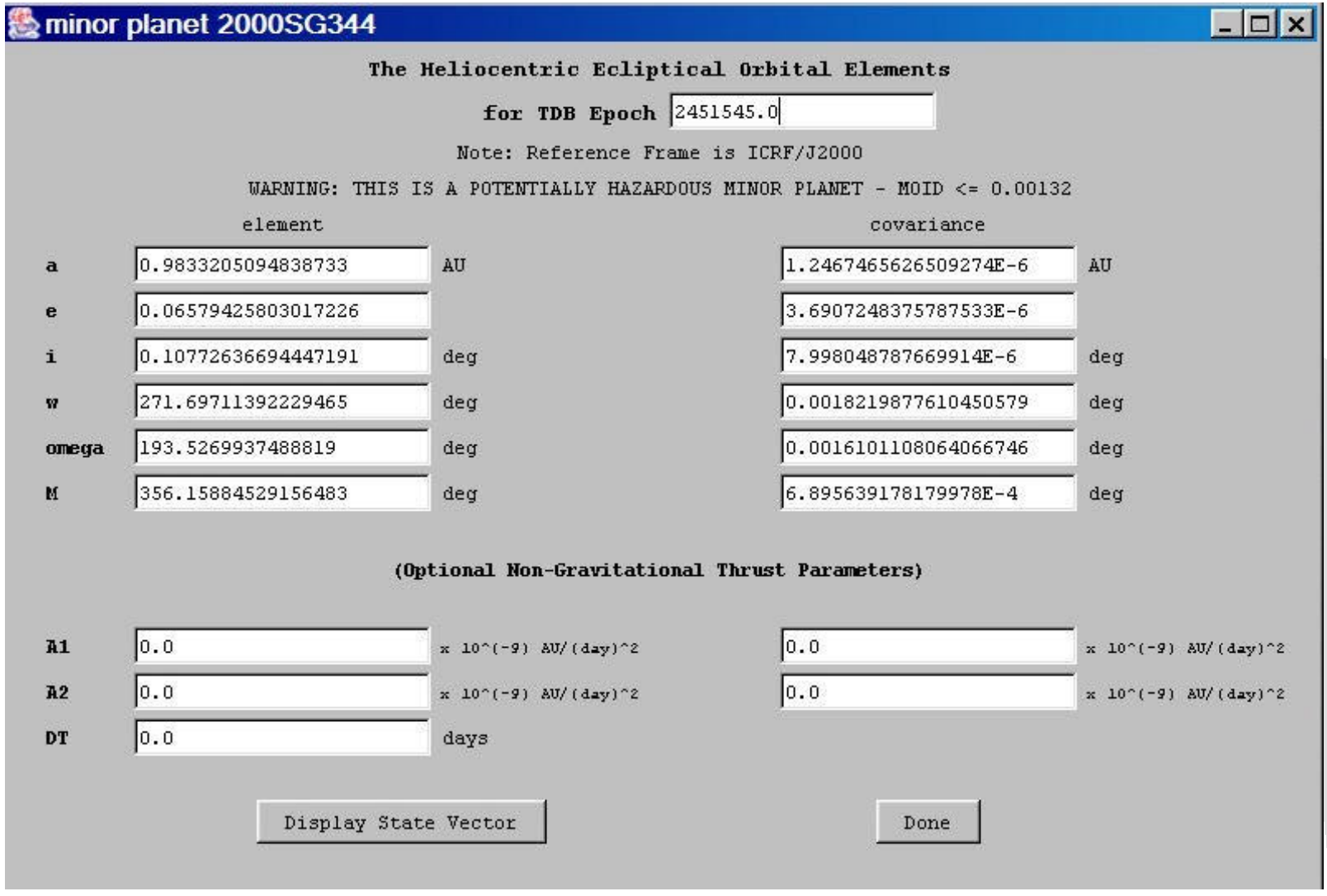
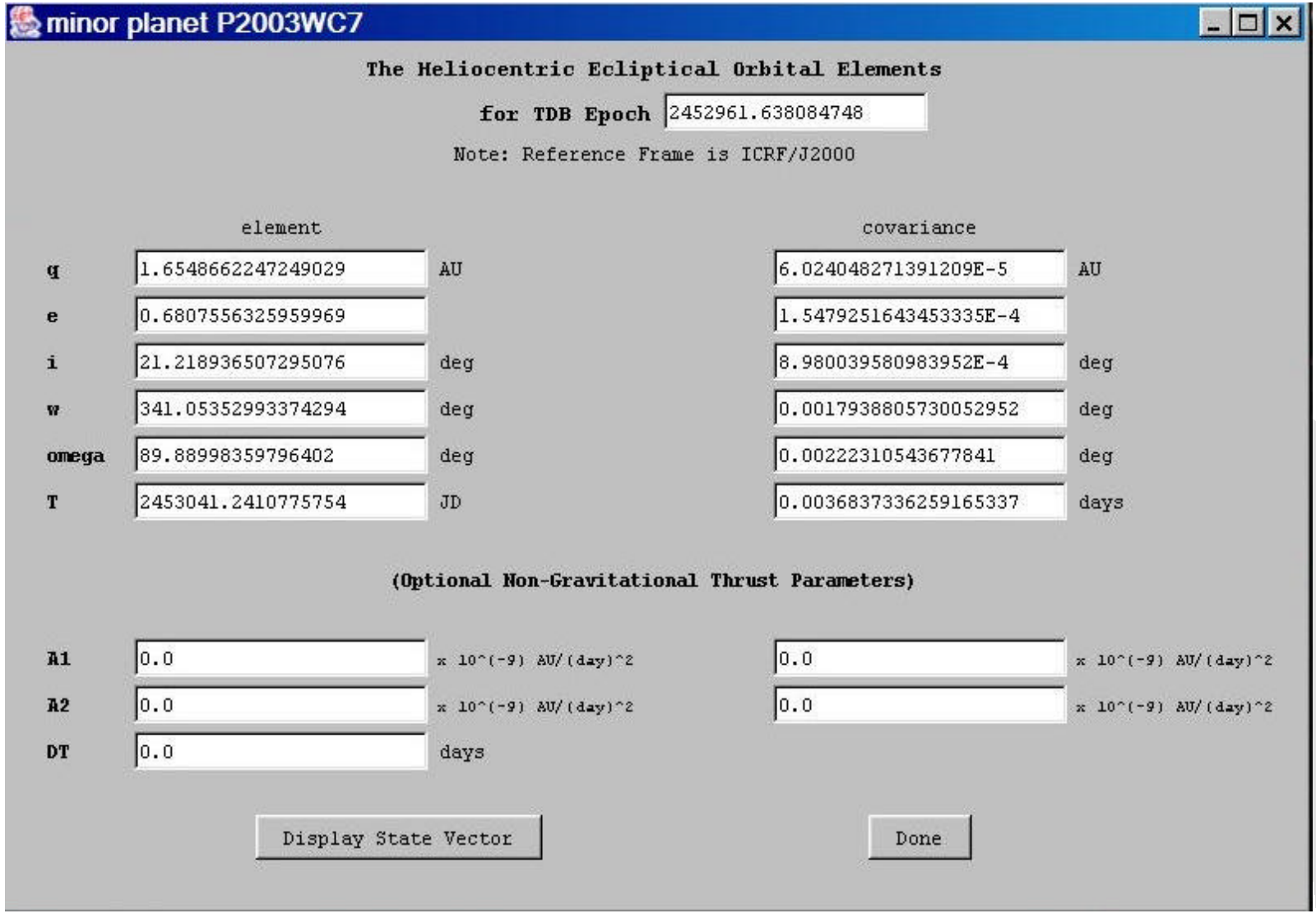
Level Two Menu: *Propogate the current orbit to a new epoch*


minor planet 2000SG344
The Heliocentric Ecliptical Orbital Elements
for TDB Epoch 2451545.0
Note: Reference Frame is ICRF/J2000
WARNING: THIS IS A POTENTIALLY HAZARDOUS MINOR PLANET - MOID <= 0.00132
element
covariance
a 0.9833205094838733 AU 1.2467465626509274E-6 AU
e 0.06579425803017226 3.6907248375787533E-6
i 0.10772636694447191 deg 7.998048787669914E-6 deg
w 271.69711392229465 deg 0.0018219877610450579 deg
omega 193.5269937488819 deg 0.0016101108064066746 deg
M 356.15884529156483 deg 6.895639178179978E-4 deg
(Optional Non-Gravitational Thrust Parameters)
A1 0.0 x 10^(-9) AU/(day)^2 0.0 x 10^(-9) AU/(day)^2
A2 0.0 x 10^(-9) AU/(day)^2 0.0 x 10^(-9) AU/(day)^2
DT 0.0 days
Display State Vector
Done

Level Two Menu: *Display Current Orbit*



Level Two Menu: *Manually specify an orbit for this minor planet*

- User can specify either state vector or orbital elements (plus covariances)
- Allows evaluation or adoption of non-CODES derived orbits
  - Calculate residuals for comparison
  - Provide initial orbit for best-fit refinement
  - Calculate an ephemeris
  - Conduct a linear collision analysis
- Allows trial and error determination of DT cometary thrust parameter

Level Two Menu: *Import a minor planet orbit from the MPCORBcr or COMET catalogs*

Allows CODES to read the orbital elements of a minor planet directly from the appropriate MPC catalog:

- Provide initial orbit for best-fit refinement
  - Add estimated covariances
  - Add or determine cometary thrust parameters
- Calculate an ephemeris
- Conduct a collision analysis

Level Two Menu: *Compare observations to positions of known minor planets*

Generates a list of those minor planets in the MPCORBcr or COMET catalog most nearly matching the observations of this minor planet

- Use two-body or n-body mechanics
- Select "medium" or "high" integration accuracy
- Narrow n-body asteroid candidate search on basis of
  - population (NEA, main belt, Centaur/TNO)
  - absolute magnitude

For each entry:

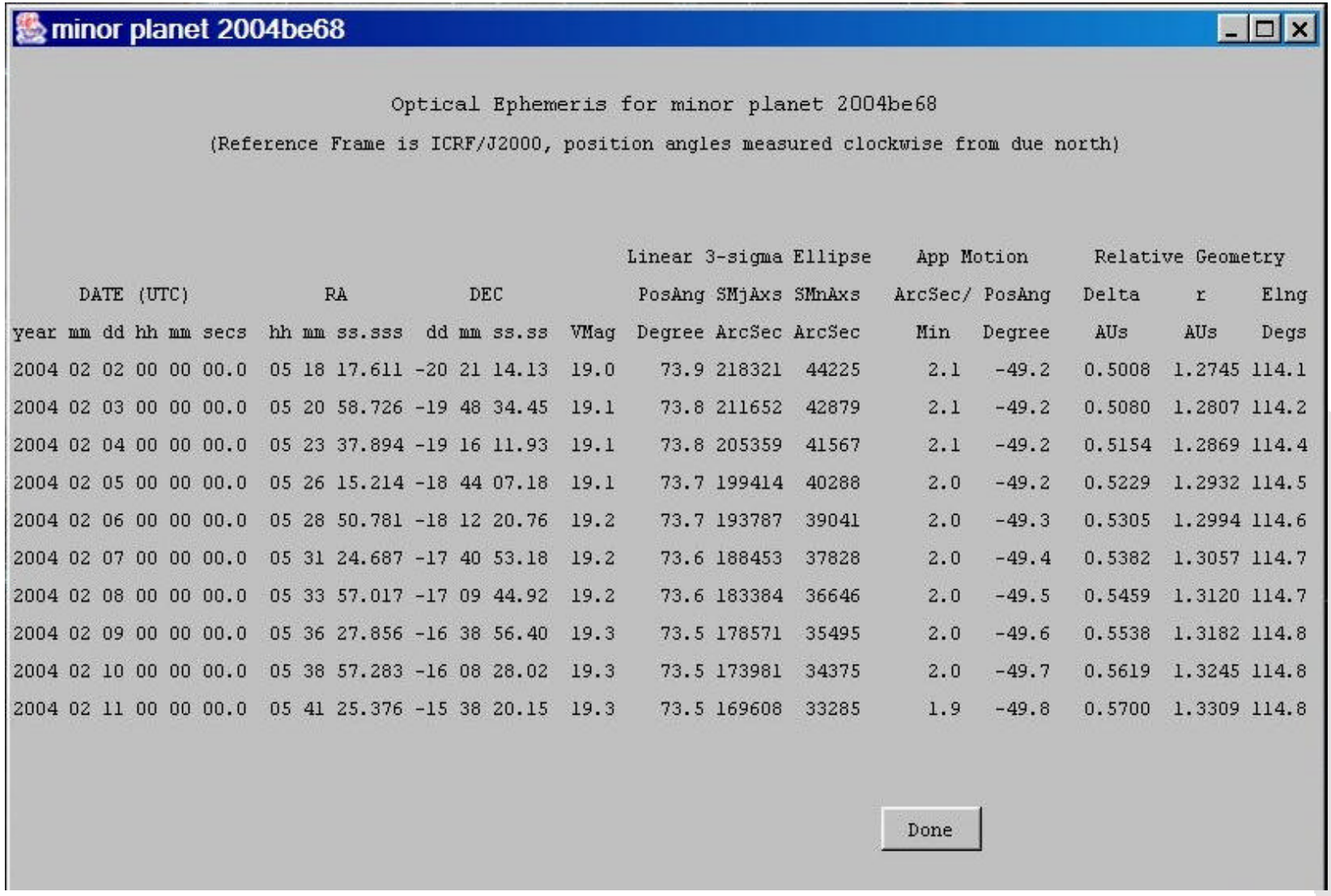
- Extracts orbital elements from catalog
- Predicts astrometric position at time of each observation
- Eliminated if either
  - RMS residual > 3 degrees
  - visual mag. residual > 2

Candidates output to screen and text file

Level Two Menu: *Generate an optical ephemeris*

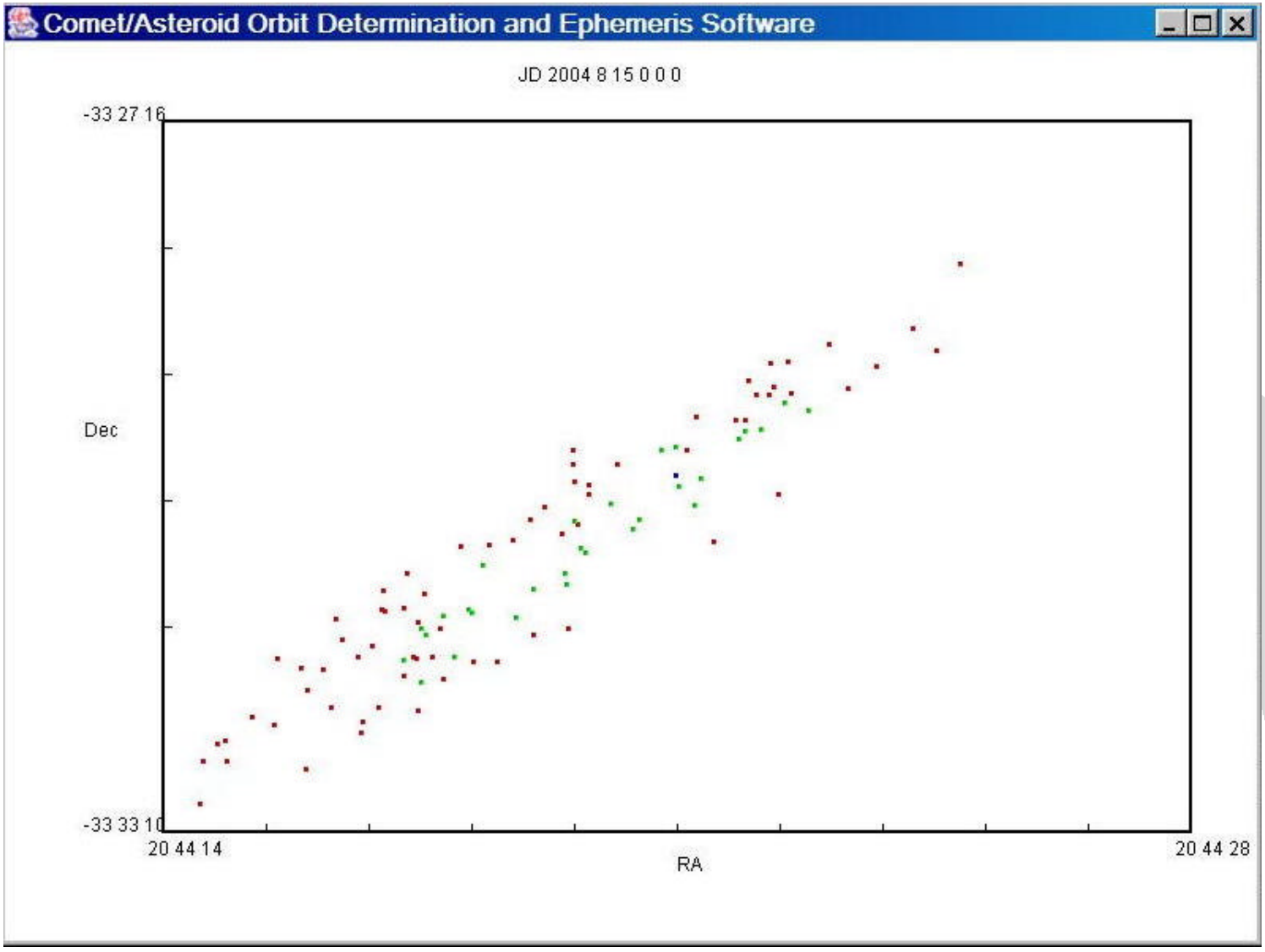
- Geocentric/topocentric ephemerides for desired range of dates
- Tabular presentation
  - nominal values for each desired date
  - major axis/minor axis/orientation angle of linear covariance ellipse
- Scatterplot presentation
  - displays predicted RA/Decs based on variant orbits generated by Observational Monte Carlo or Statistical Ranging
  - Color-coded by RMS residual of variant orbit to illustrate most likely positions
  - Displays non-linear observation space for precovery/recovery

Level Two Menu: *Generate an optical ephemeris (cont)*


minor planet 2004be68
Optical Ephemeris for minor planet 2004be68
(Reference Frame is ICRF/J2000, position angles measured clockwise from due north)
Done

	DATE (UTC)					RA			DEC			Linear 3-sigma Ellipse			App Motion		Relative Geometry		
												PosAng	SMjAxs	SMnAxs	ArcSec/	PosAng	Delta	r	Elng
year	mm	dd	hh	mm	secs	hh	mm	ss.sss	dd	mm	ss.ss	VMag	Degree	ArcSec	ArcSec	Min	Degree	AUs	AUs	Degs
2004	02	02	00	00	00.0	05	18	17.611	-20	21	14.13	19.0	73.9	218321	44225	2.1	-49.2	0.5008	1.2745	114.1
2004	02	03	00	00	00.0	05	20	58.726	-19	48	34.45	19.1	73.8	211652	42879	2.1	-49.2	0.5080	1.2807	114.2
2004	02	04	00	00	00.0	05	23	37.894	-19	16	11.93	19.1	73.8	205359	41567	2.1	-49.2	0.5154	1.2869	114.4
2004	02	05	00	00	00.0	05	26	15.214	-18	44	07.18	19.1	73.7	199414	40288	2.0	-49.2	0.5229	1.2932	114.5
2004	02	06	00	00	00.0	05	28	50.781	-18	12	20.76	19.2	73.7	193787	39041	2.0	-49.3	0.5305	1.2994	114.6
2004	02	07	00	00	00.0	05	31	24.687	-17	40	53.18	19.2	73.6	188453	37828	2.0	-49.4	0.5382	1.3057	114.7
2004	02	08	00	00	00.0	05	33	57.017	-17	09	44.92	19.2	73.6	183384	36646	2.0	-49.5	0.5459	1.3120	114.7
2004	02	09	00	00	00.0	05	36	27.856	-16	38	56.40	19.3	73.5	178571	35495	2.0	-49.6	0.5538	1.3182	114.8
2004	02	10	00	00	00.0	05	38	57.283	-16	08	28.02	19.3	73.5	173981	34375	2.0	-49.7	0.5619	1.3245	114.8
2004	02	11	00	00	00.0	05	41	25.376	-15	38	20.15	19.3	73.5	169608	33285	1.9	-49.8	0.5700	1.3309	114.8

Level Two Menu: *Generate an optical ephemeris (cont)*



Level Two Menu: *Linear Collision Analysis*

Requires state vector and (if impact probability desired) covariances

Algorithm:

- Propogate state vector forward from epoch to desired end-point
  - at end of each integration step, test distance to each possible target (Sun, Moon, nine major planets)
    - if (distance < target radius) => **collision**
      - use bisection to isolate
      - propogate covariances to determine impact probability
    - else if (distance > target radius) and (distance < user-specified threshold) and (first derivative changes sign)
      - use bisection to isolate minimum
      - if (distance at minimum < target radius) => **collision**
        - use bisection to isolate
        - propogate covariances to determine impact probability
      - if (distance at minimum > target radius) => **near miss**
        - propogate covariances to determine impact probability

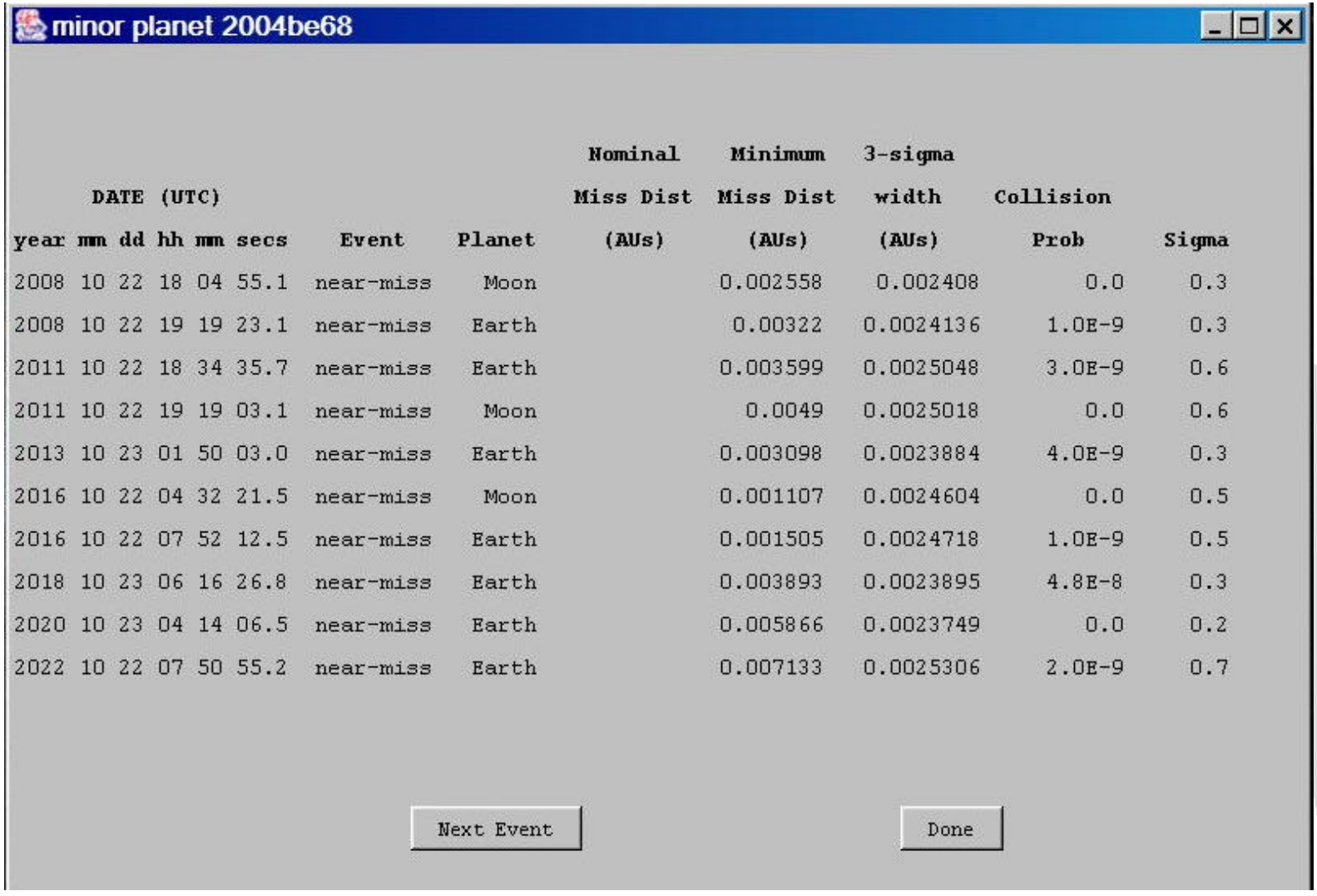
Level Two Menu: *Non-Linear Collision Analysis*

Primary options requires state vector and covariances, plus all observations

Algorithm:

- Creates user-specified number of Virtual Asteroids
  - Distributed normally in observation space about the nominal state vector
  - Spaced along the Line of Variations
- Each VA propogated forward from epoch to desired end-point
  - collisions/near-misses noted as in linear analysis
  - events with ((scaled moid - 3-sigma width of covariance ellipse) < threshold) are sorted by target, date, and stretching into trails
- The minimum approach or folding point for each trail is retained
  - use differential correction to test for collision/near-miss
  - if differential correction fails, or in case of an interrupted return, create a "dense sampling" (100 VAs around minimum/folding point), look for collision/nearest miss

Level Two Menu: *Collision Analysis (output to text and file)*



Level Two Menu: *Collision Analysis (Considerations)*

- Analysis generally similar to Milani, Chesley, Chodas, and Valsecchi in *Asteroids III*
- Results thus far comparable with Sentry and NEODyS Risk Page despite some algorithmic differences
  - CODES collision analysis performed (and results quoted) in 3-space vs. collision plane
  - Trails defined slightly differently
  - CODES differential correction performed along LOV
  - CODES uses “dense sampling” rather than interpolation
  - Independently-derived epoch state vectors and covariances

Comparison: CODES vs. Sentry vs. NEODyS

2004 BE68 with 39 observations (2004-Jan-27.09321 to 2004-Feb-01.48334)

Date (UTC)	Predicted Miss Dist. (er)	1-sigma width (er)	Collision Probability	LOV Sigma
2008 10 22.805	75.5	18.9	1.0E-9	0.3
2008 10 22.895	72.0	20.1	7.4E-10	0.8
2011 10 22.774	84.4	19.6	3.0E-9	0.6
2011 10 22.767	86.5	21.1	2.5E-11	1.4
2013 10 23.076	72.7	18.7	4.0E-9	0.3
2013 10 23.074	70.8	20.1	4.8E-10	0.8
2016 10 22.328	35.3	19.3	1.0E-9	0.5
2016 10 22.32	26.0	14.2	6.4E-8	1.2
2016 10 22.313	36.4	20.8	2.4E-8	1.2
2018 10 23.261	91.3	18.7	4.8E-8	0.3
2021 10 22.681	11.0	20.6	9.0E-8	1.1
2022 10 22.327	167.3	19.8	2.0E-9	0.7
2024 10 22.201	64.2	19.4	0.0	0.5
2024 10 22.190	66.9	20.8	3.0E-10	1.3
2026 10 23.018	2.3	46.8	0.0	0.4
2026 10 23.01	1.2	13.9	5.3E-8	1.1
2026 10 23.013	1.8	20.4	9.0E-8	1.1
2029 10 22.521	14.6	19.2	0.0	0.5
2029 10 22.50	8.3	14.2	1.8E-8	1.2
2029 10 22.501	11.6	20.7	2.9E-8	1.2
2031 10 23.322	0.0	27.5	1.0E-9	0.4
2031 10 23.31	0.1	13.8	4.8E-8	1.1
2031 10 23.322	1.1	18.5	8.1E-8	1.0
2034 10 22.905	28.8	19.4	0.0	0.5
2034 10 22.87	20.9	14.1	3.2E-8	1.2
2034 10 22.867	29.3	20.6	2.0E-8	1.2

CODES

Level Two Menu: *Collision Analysis (Statistical Ranging)*

- A Monte Carlo collision analysis option is also available for use with trajectories generated by Statistical Ranging (or by Observational Monte Carlo)
  - Trajectories are integrated from epoch to desired endpoint; collisions/near-misses are noted, but no use of trails
  - Impact probability determined simply as (number of impacting trajectories) / (total number of trajectories)
- Most useful for cases such as AL00667/2004 AS1, when threat assessment is required but only a very short observation arc is available

Level Two Menu: *Change the number of perturbing bodies*

Determines what perturbing bodies are used in n-body numerical integration

- Sun, Moon, nine planets
- Sun, Moon, nine planets, Ceres, Pallas, and Vesta (default)
- Sun, Moon, nine planets, and 235 asteroids
  - much slower processing
- Sun, Moon, nine planets, and 300 asteroids
  - Much slower processing

CODES uses

- JPL DE405 Planetary Ephemeris
- Mean asteroid orbital elements

Level Two Menu: *Set the radius/visual brightness parameters*

- Useful if orbital elements are imported or user-specified
  - slope parameter and absolute magnitude otherwise unavailable
  - allows estimated visual magnitudes in ephemerides
- Radius critical in processing bounce point of radar observations
  - usually determined from visual brightness data as part of best-fit orbit determination
  - if no brightness data, should be set manually prior to orbit determination
    - default is 1 km
    - comets - set to estimated bounce point (coma radius?)

System and Software Requirements

CODES is written in pure Java - compiled bytecode will run on any system for which a Sun Virtual Machine exists

System Requirements:

- approximately 150 MB of disk storage (including DE405 files)
- 256 MB (or greater) RAM
- internet access (for download of observation files, MPC catalogs, EOP files, and updated ObsCode files)

Software requirements (all available for free download):

- Java 1.4.1 (or higher) runtime environment
- compiled CODES bytecode and (optional) source code
- JPL DE405 planetary ephemeris files (ASCII versions)
- IERS Earth Orientation Parameter files

Where can I find CODES?

Web site is http://home.earthlink.net/~jimbaer1/

- Fully-documented User's Manual
- Links to all required software

Suggestions for future enhancements are welcome!
(jimbaer1@earthlink.net)